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Benefits and limitations to straw- and plastic-film mulch on maize yield and water use efficiency: A meta-analysis across hydrothermal gradients

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ABSTRACT

Ridge-furrow mulching can reduce soil evaporation and conserve rainfall, thereby increasing crop yield and water use efficiency (WUE) in dryland cropping systems. In this study, we collected 837 observations from 50 published papers and used meta-analysis to investigate whether ridge-furrow and mulching practices are equally effective on maize yield, WUE and evapotranspiration (ET) across a range of precipitation and temperature gradients and soil types in China. Five practices were included: (i) straw mulch on flat plots (SMF), (ii) straw mulch on ridge-furrow plots (SMR), (iii) plastic mulch on flat plots (PMF), (iv) plastic mulch on ridge-furrow plots (PMR), and (v) flat plots without mulch, which was used as a control (CK). The meta-analysis showed that both straw mulch and plastic mulch significantly increased maize yields and WUE (except for SMR), and that plastic mulch was more effective than straw mulch in increasing yields, particularly in cold and dry environments. PMR has the highest yields and is more effective in clay loam than in silt loam soils. Straw mulch, but particularly plastic mulch, increased the soil moisture compared to the CK, while plastic mulch increased soil temperature, mainly in spring. However, the positive effect of plastic mulch on maize yield diminished with increasing mean growing-season temperature and precipitation, reaching zero (similar to the CK of no mulch and flat plots) when the growing-season precipitation was greater than 770 mm and the mean growing-season air temperature exceeded 24 °C. The small benefit of straw mulch (on average about 12%) was similar across the precipitation and temperature gradients, including when the benefits of plastic mulch reached zero. While our analysis has shown the benefits of ridge-furrow plastic mulch on yield and water-use efficiency, it has also highlighted the limitations of the benefits. The results provide a guide to the regions where plastic-film mulch and ridge-furrow planting are likely to improve maize yields and regions where the benefits are likely to be limited.

1. Introduction

Global food demand is projected to double by 2050 compared to that at the beginning of this century (Tilman et al., 2011), but there will be limited or no increase in the area of arable land or water for irrigation. The situation is very severe in China due to its large population; the available cropland is only 0.1 ha per capita (Wu, 2001) and the available water per capita is only one quarter the world average (Shan et al., 2000). Water shortage is even more severe in northern China, which has 65% of the total arable land, but less than 20% of total national available water resources (Deng et al., 2006). Because of the lack of water resources for irrigation in northern China, precipitation is the main source of water for crop growth (Ye and Liu, 2012). To support the large and growing population in China, the increase of food production must be based on improving crop yields and water use efficiency of existing cropping systems (Deng et al., 2006; Godfray et al., 2010).

Maize has become China's largest crop; the area and yield reached 38 million hectares and 224 million tons in 2015 (Li et al., 2017). It is mainly grown in semi-arid and arid regions, both rainfed and with irrigation. In semi-arid and arid areas, the precipitation is mainly concentrated in July to September, that is in the mid- to late growth period. Water deficits and cold temperatures in the early stages of growth affect the emergence and early growth of maize, thereby affecting the crop

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yield (Wang et al., 2010). Different *in situ* soil and water management practices, such as mulching and ridge-furrow tillage, have been developed and shown to be effective in increasing crop yields and water use efficiency (WUE) in water-limited environments of China (Gan et al., 2013; Wang et al., 2015; Wang and Shangguan, 2015; Wang et al., 2016a). For maize (*Zea mays* L.), these practices include alternating ridges and furrows with only the ridges covered with plastic film (Li et al., 2001; Wang et al., 2010), alternating mulched and bare rows without ridges (Liu et al., 1989), flat plots all mulched with plastic film (Zhang et al., 2004), straw mulching, and in recent decades the commonly used technique of double ridges and furrows mulched with plastic film (Zhang et al., 2011). Both straw and plastic mulch have been shown to reduce soil evaporation and improve water use efficiency, while plastic mulch can also improve the soil temperature in spring, allowing earlier planting and quicker development (Sui et al., 1992; Chen et al., 2007; Liu et al., 2014; Wang et al., 2016a).

Since the main effects of plastic mulch are to reduce soil evaporation and increase soil temperature, it is likely that the positive effects of plastic mulch will diminish as precipitation and temperature increase. A few studies have shown that plastic-film mulch increased maize yield and its stability more as the hydrothermal conditions became more severe (Qin et al., 2015; Wang et al., 2016a). Several recent meta-analyses have focused on which mulch and tillage practices have the greatest effect on crop yield, water use efficiency and nitrogen use efficiency. The analyses showed that plastic mulch is more effective than straw mulch (Qin et al., 2015), and ridge-furrow plastic mulch most consistently increases crop yields and WUE (Wang and Shangguan, 2015; Zhang et al., 2017). Our meta-analysis aimed to quantify the effects of different mulch and tillage practices on maize yields, WUE and evapotranspiration across a series of hydrothermal gradients. Compared to the previous studies, our meta-analysis is novel in that it (1) includes a vast region of China and evaluates the effects of both mulching (straw vs. plastic film) and tillage practices (flat vs. ridge furrow plots); (2) estimates not only the benefits, but also the limitations to plastic mulching by rainfall and temperature, i.e., under which precipitation and temperature conditions do the positive effects of plastic mulching and ridge-furrow tillage on maize disappear; and (3) evaluates the effects of mulching and ridge-furrow tillage in different soil types and different nutrients levels. As much of the literature on mulching and tillage are published in Chinese, their inclusion in our analysis extends the scope of the previous analyses that focused mainly on studies published in English.

2. Methods

2.1. Data search and collection

Relevant literature of the grain yield of maize with different mulching and tillage practices was searched using the online databases of the Chinese Academy of Sciences (http://www.isiknowledge.com/ and http://www.cnki.net/) and Google Scholar (http://scholar.google.com/). The search terms were ‘mulch’ or ‘mulching’, ‘maize’ and ‘yield’ in the article title, abstract, and keywords. Publications in both Chinese and English were included. To be considered, the publications had to fit the following criteria: (1) the studies had to be conducted in the field and include both control (no mulch and flat plots, CK) and treatments (either flat or ridge-and-furrow tillage and/or straw or plastic-film mulch) (Table 1); (2) the maize was not be irrigated at any time within the growing season; (3) the location and year of the experiment were provided; (4) for factorial experiments, only data from non-mulched and mulched treatments were used and data from interactions among treatments, such as fertilization × straw mulch or plastic-film mulch, were excluded; (5) data without a control treatment, that is sown on flat plots without mulch, were only used for regression analysis, not in the meta-analysis.

The mean, standard deviation (*SD*) or standard error (*SE*), and the number of replicates of the treatments were directly acquired from the publication or calculated using the following formula (Rusinamhodzi et al., 2011):

$$SD = SE \times \sqrt{n} \tag{1}$$

As some studies did not report the *SD*, we calculated the average coefficient of variation (*CV*) within each dataset and then estimated the missing *SD* via the following equation (Wang et al., 2015):

$$SD = \overline{X} \times CV \tag{2}$$

where $\overline{X}$ is the mean of the treatment (mulch and/or tillage treatments) and control group (CK, no mulch and flat plots).

In addition, the site mean growing-season temperature and precipitation were also obtained from the publication. If no meteorological information was given in the publication, we obtained the mean growing-season temperature and precipitation from the nearest meteorological station (the Chinese meteorological data network, http://data.cma.cn/user/toLogin.html). In total, 963 observations of the five management practices were obtained from 90 published papers (Tables S1 and S2, Supplementary Information). Of these, 837 observations from 50 field experiment studies that included both CK (no mulch and flat plot) and treatments (mulch and tillage) were used in the meta-analysis (Table 2). The other 126 observations from 40 field experiments did not include CK and were not used in the meta-analysis, but the data were used for analyzing the relationships between yield and temperature, and yield and precipitation. In summary, all data in Table S1 were used to analyze the relationships between yield and temperature/precipitation; only data in Table 2 (a subset of Table S1) were used for meta-analysis. In the meta-analysis, each treatment was compared to its corresponding CK. For example, yield data of the straw mulch planted in flat plots (SMF) were compared to CK data obtained from the same studies. CK data obtained from studies without SMF treatment were excluded because these studies may be located in areas with very different growing-season precipitation or/and temperatures (thus falsely increasing or decreasing the average values of CK). In some studies, several levels of a single treatment such as 1–9 t dry mass of straw ha^{-1} were applied (Table 1). Therefore, the number of observations (*n*) shown in Table 2 may be different for each treatment and its corresponding CK.

Soil type, soil organic matter, nitrogen, phosphorus and potassium contents were collected for sites for which this information was available (Table 3 and Table S3). Data shown in Table S3 are for all datasets used for regression analyses, while only the subset used in the meta-analysis is shown in Table 3. Three soil types, namely clay loam, silt loam and clay were identified at the study sites. Most of the sites (96.6%) have a loam soil type which drains well, but relatively poor soil nutrient content (Gong, 1999).

The ET, WUE, soil water content (gravimetric water content in % measured at 0–0.2 m soil depth), and soil temperature (measured at 0–0.2 m soil depth) data under different treatments were also collected from individual studies where these data were available. Soil water data were available for all five practices, while soil temperature data were not available in the straw-mulch treatments. The field sites used in the meta-analysis were generally in central and northern China (Fig. 1), characterized by arid and semiarid climates.

2.2. Meta-analysis

Meta-analysis is a formal quantitative statistical method to summarize results from independent experimental studies (Hedges et al., 1999). In this study, we used the effect size (*R*) to quantify the effect of mulch and ridge-furrow treatments on maize yield, WUE and ET:

$$R = \overline{X}e / \overline{X}c \tag{3}$$

where $\overline{X}e$ is the mean of the treatment group (mulch and/or tillage

Table 1
Description of the five tillage and mulch treatments used in the field experiments analyzed in the meta-analysis.

Acronym	Mulching treatment*	Description
CK	No mulch + Flat	Maize sown on a flat plot without ridges and furrows and without mulch (control).
SMF	Straw mulch + Flat	The straw (1–9 t dry mass ha^{-1}) chopped or unchopped and evenly spread over the soil surface of a flat plot.
SMR	Straw mulch + Ridge-furrow	Field formed into ridges and furrows (of different heights and widths) with maize planted in the furrows or the edge of the ridges, with straw chopped or unchopped and spread over the soil surface of furrow.
PMF	Plastic-film mulch + Flat	Field remains flat, but either fully mulched with clear thin (~8 μm) plastic film and holes punched in the plastic film to facilitate infiltration of rainfall, or a gap left between mulched strips (i.e. half mulched). Maize is planted through holes punched in the plastic, near the edges of the strip in the half-mulched plots.
PMR	Plastic-film mulch + Ridge-furrow	Field formed into ridges and furrows and fully mulched or only the ridges are mulched. Maize is planted through holes punched in the furrows or the edge of the ridges.

* In about 70% of the studies, mulch was applied around 10 days before sowing. In the remaining 30% of studies the mulch was applied at sowing or one month before sowing. The straw was the residue from the previous crop including the maize straw from the previous year in multi-year experiments. The tillage system in flat plots was ploughing the soil to improve the soil structure, promote seed germination and root growth. The ridge furrow system was established before or simultaneously with each sowing.

treatments) and $\overline{X}c$ is the mean of the control group (CK, no mulch and flat plots). To express the treatments effect on a common scale, the natural logarithm of the response ratio was used (Hedges et al., 1999):

$$\ln R = \ln(\overline{X}e/\overline{X}c) = \ln\overline{X}e - \ln\overline{X}c \tag{4}$$

The variance (V) of ln$R$ is:

$$V(\ln R) = \frac{(Se)^2}{n(\overline{X}e)^2} + \frac{(Sc)^2}{n(\overline{X}c)^2} \tag{5}$$

where Se and Sc are the corresponding standard deviations, and n is the number of replicates. The weighted average of the logarithmic response ratios were calculated for all independent studies:

$$\ln\overline{R} = \frac{\sum_{i=1}^{m} w_i \ln R_i}{\sum_{i=1}^{m} w_i} \tag{6}$$

where w_i is the weight for study i, calculated as the inverse of the sample variance ($w_i = 1/V_i$). Thus, studies with large variance among replicates have smaller weight. lnR_i is the logarithmic response ratio for study i, m is the number of studies, and ln$\overline{R}$ is the mean effect size.

In this study, we used a fixed effect model because the estimate of the mean pooled variances for maize yield, WUE, ET and soil types (clay loam, silt loam and clay) were less than or equal to zero. The MetaWin2.1 was applied to generate 95% confidence intervals around the logarithmic response ratios with 4999 iterations. If the values of the 95% confidence interval for the effect size of a variable did not overlap with zero, the effects of mulch/tillage on the variable studied were considered statistically significant; otherwise the treatment effect was not significant. Similarly, if the values of the 95% confidence interval for the effect size of a treatment did not overlap with other treatments, the effects of two treatments were considered statistically significant; otherwise the treatment effects were not significant between each other.

2.3. Statistical analysis

Regression analysis was used to analyze the relationships between observed maize yield and growing-season (late April to early October) precipitation and temperature under the five management practices. In the meta-analysis, we also calculated the yield response ratio (lnR_i) for each experimental study (see Eq. (4)). The relationships between response ratios and environmental variables (temperature, precipitation, soil organic matter, nitrogen, phosphorus and potassium) were also evaluated using regression analysis. Covariance analysis was used to test the significance of the difference in the slopes and intercepts between the equations from the different linear fits. These analyses were performed using the statistical software program SPSS 22.0 (SPSS, 2015).

3. Results

3.1. Yield, WUE, and ET in the different mulch and tillage treatments

Maize yields ranged from 170 to 15,700 kg ha^{-1} in the different mulch and tillage treatments in our meta-analysis dataset (Table 2). The meta-analysis showed that all four mulch and tillage treatments significantly increased maize yields (mean effect sizes were greater than 0) relative to the respective CK (Fig. 2); straw mulched flat plots (SMF) by

Table 2
The number of observations (n), mean and range of the grain yield, water use efficiency (WUE) and evapotranspiration (ET) and their variabilities (measured as the coefficient of variation, CV) for the five mulch and tillage treatments analyzed in the meta-analysis: straw mulch on flat plots (SMF), plastic-film mulch on flat plots (PMF), straw mulch on ridge-furrow plots (SMR), plastic-film mulch on ridge-furrow plots (PMR) and their corresponding check plots with no mulch and flat plots (CK). The CV was not available for all observations, particularly measurements of WUE and ET with ridge-furrow tillage. Since these observations were collected from independent field studies, the statistical analysis is not shown in the table. The statistical test, i.e. meta-analysis, was used to quantitatively summarize results from these independent observations (see Fig. 2).

Treatment	Yield (kg ha^{-1})				WUE (kg ha^{-1} mm^{-1})				ET (mm)			
	n	Mean	Range	CV (%)	n	Mean	Range	CV (%)	n	Mean	Range	CV (%)
CK	146	6070	170–12606	7.69 (n = 48)	94	15.9	0.4–41.7	6.74 (n = 10)	53	343	185–507	7.08 (n = 6)
SMF	61	6620	3060–12750	4.56 (n = 14)	60	17.8	8.8–29.4	4.70 (n = 13)	24	349	257–491	4.19 (n = 13)
CK_{SMF}	52	6091	1640–11610	5.10 (n = 14)	51	15.2	4.3–27.3	3.22 (n = 13)	15	379	253–507	3.66 (n = 13)
PMF	43	9013	4589–14666	7.33 (n = 25)	21	25.9	11.1–51.9	13.30 (n = 2)	23	331	221–459	13.98 (n = 2)
CK_{PMF}	34	6799	536–12606	8.40 (n = 25)	18	17.4	1.3–41.7	15.30 (n = 2)	19	336	185–456	15.67 (n = 2)
SMR	28	5583	2998–9000	5.27 (n = 14)	3	19.7	15.3–24.1		3	282	263–301	
CK_{SMR}	28	5004	2821–8133	7.30 (n = 14)	3	20.4	14.7–27.1		3	290	261k330	
PMR	142	9522	1120–15698	5.03 (n = 50)	69	29.0	1.9–54.6	6.08 (n = 4)	64	323	212–416	
CK_{PMR}	93	6013	170–12606	7.10 (n = 50)	41	16.5	0.4–41.7	7.41 (n = 4)	37	326	185–417	

Table 3
Characterization of soil type, defined according to the FAO classification system (1988) and as classified for the meta-analysis, the concentration of organic matter, available nitrogen, available phosphorus and available potassium in the upper 0.2 m soil, and the range of growing-season precipitation and temperature at the experimental sites used in the different treatments in the meta-analysis. P, mean growing-season precipitation; T, mean growing-season air temperature; N, nitrogen; P, phosphorus; K, potassium.

Treatment	P (mm)	T (°C)	Soil type	Organic matter ($g\ kg^{-1}$)	Available N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)
CK	160–640	12.3–21.7	Los-Orthic Entisols, Clay loam	7.1–21.1	19.2–128.0	7.0–56.0	106–116
	150–640	12.3–23.1	Haplic Kastanozem, Silt loam	9.6–21.1	23.0–89.0	3.2–56.0	96–248
	180–580	17.8–21.7	Hap–Udic Luvisol, Silt loam	9.1–27.1	29.4–76.4	0.8–6.9	95–125
	450–750	21.2–27.4	Aquic Cambisol, Clay				
SMF	160–560	15.5–23.1	Haplic Kastanozem, Silt loam	11.8–12.1	79.69	14.4–31.3	145
	260–430	16.5–17.7	Los-Orthic Entisols, Clay loam	7.1	19.2	11.9	106
	150–320	16.7–22.3	Haplic Calcisol, Sandy loam	5.3	13.5	2.1	197
	180–580	19.1–21.7	Hap-Udic Luvisol, Silt loam	27.1	76.4	2.8	95
	450–750	21.2–27.4	Aquic Cambisol, Clay				
CK_{SMF}	160–560	15.5–23.1	Haplic Kastanozem, Silt loam	11.8–12.1	79.69	14.4–31.3	145
	260–430	16.5–17.7	Los-Orthic Entisols, Clay loam	7.1	19.2	11.9	106
	150–320	16.7–22.3	Haplic Calcisol, Sandy loam	5.3	13.5	2.1	197
	180–580	19.1–21.7	Hap-Udic Luvisol, Silt loam	27.1	76.4	2.8	95
	450–750	21.2–27.4	Aquic Cambisol, Clay				
PMF	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	7.6	23.1	22.4	116
	190–500	14.7–23.1	Haplic Kastanozem, Silt loam	11.0–19.4	33.0–89.0	3.2–31.3	117–248
	150–320	16.7–22.3	Haplic Calcisol, Sandy loam	5.3	13.5	2.1	197
	180–580	17.8–21.7	Hap-Udic Luvisol, Silt loam	9.1–10.5	29.4–53.7	0.8–6.9	95–125
CK_{PMF}	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	7.6	23.1	22.4	116
	190–500	14.7–23.1	Haplic Kastanozem, Silt loam	11.0–19.4	33.0–89.0	3.2–31.3	117–248
	150–320	16.7–22.3	Haplic Calcisol, Sandy loam	5.3	13.5	2.1	197
	180–580	17.8–21.7	Hap-Udic Luvisol, Silt loam	9.1–10.5	29.4–53.7	0.8–6.9	95–125
SMR	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	15.1–21.2	23.0–128.0	7.0–56.0	
	160–560	15.5–23.1	Haplic Kastanozem, Silt loam	11.9–21.1	23.0–84.0	28.0–56.0	96
CK_{SMR}	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	15.1–21.2	23.0–128.0	7.0–56.0	
	160–560	15.5–23.1	Haplic Kastanozem, Silt loam	11.9–21.1	23.0–84.0	28.0–56.0	96
PMR	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	7.6–21.2	23.1–128.0	7.0–56.0	114–116
	160–560	14.7–23.1	Haplic Kastanozem, Silt loam	9.6–21.1	23.0–89.0	3.2–56.0	96–248
	180–580	17.8–21.7	Hap-Udic Luvisol, Silt loam	9.0–10.5	53.7	6.9	125
CK_{PMR}	160–650	12.3–21.7	Los-Orthic Entisols, Clay loam	7.6–21.2	23.1–128.0	7.0–56.0	114–116
	160–560	14.7–23.1	Haplic Kastanozem, Silt loam	9.6–21.1	23.0–89.0	3.2–56.0	96–248
	180–580	17.8–21.7	Hap-Udic Luvisol, Silt loam	9.0–10.5	53.7	6.9	125

9%, straw mulched ridge-furrow plots (SMR) by 12%, plastic mulched flat plots (PMF) by 33% and plastic mulched ridge-furrow plots (PMR) by 58% relative to their respective checks (CK) (Table 2). The mean effect sizes of the mulch/tillage practices were ranked in the order of PMR > SMR = SMF (Fig. 2a). The mean effect of PMR was 0.282 (95% CI: 0.278–0.286), PMF it was 0.258 (0.097–0.420), SMR it was 0.121 (0.100–0.143), and SMF it was 0.106 (0.093–0.118) (Fig. 2a), thus the maize yield in the PMR treatment was significantly greater than in the SMR and SMF treatments, but not the PMF treatment.

The meta-analysis also indicated that three of the mulch/tillage practices significantly increased WUE as compared with CK (Fig. 2b). The mean effect sizes of WUE were ranked in the order of PMF (0.356, 95% CI: 0.250–0.462) = PMR (0.262, 0.213–0.311) > SMF (0.063, 0.051–0.076) (Fig. 2b). In contrast, mulch/tillage practices had no consistent effects on ET (Table 2, Fig. 2c). There were only three very variable WUE and ET observations for SMR so that the SMR treatment had no significant effect on WUE and ET (Table 2, Fig. 2b and c).

We evaluated the impacts of mulching and ridge-furrow on maize yields in three soil types, i.e., clay loam, silt loam and clay (Fig. 3). In the PMR treatment, the mean effect size was significantly higher for the clay loam (0.538, 95%: 0.524–0.553) than for the silt loam soil (0.482, 0.464–0.501) (Fig. 3d). The mean effect size was not significantly different among the three soil types in the SMF treatment (Fig. 3a). Only two soil types i.e. clay loam and silt loam were available for PMF and SMR treatments. The mean effect sizes were not significantly different between the two soil types in both treatments (Fig. 3b–c). There were no significant relationships between soil nutrients and the response ratios (i.e. the effect of mulch and tillage in each individual study, $\ln R_i$) for the four mulch and tillage treatments (Fig. S1, Supplementary Information).

3.2. Grain yields across precipitation and temperature gradients

The grain yield increased significantly and linearly with growing-season precipitation in the SMF, PMF, PMR, and CK treatments (Fig. 4a, b, d and f), but not in the SMR treatment (Fig. 4c). While the slopes were not significantly different among CK and tillage/mulch treatments (SMF, PMF, PMR), the intercepts of PMF and PMR were significantly larger than the CK (Table 4). The yield in the tillage, mulch and check treatments increased at a mean rate of about 7.6 $kg\ ha^{-1}\ mm^{-1}$ of precipitation, but the yields were on average 2700 $kg\ ha^{-1}$ greater in the mulch/tillage treatments (Fig. 4e) than in the CK treatment (Fig. 4f) at all levels of growing-season precipitation.

Yields also significantly increased linearly with increasing growing-season temperature in the SMF, PMF, PMR, and CK treatments (Fig. 5a, b, d and f), but not in the SMR treatment (Fig. 5c). The slopes were not significantly different among CK and tillage/mulch treatments (SMF, PMF, and PMR), but the intercepts of PMF and PMR were significantly different from the CK intercept (Table 4). The yield in the tillage, mulch and check treatments increased at a mean rate of 507 $kg\ ha^{-1}\ °C^{-1}$ of mean growing-season air temperature, but the yields were 2530 $kg\ ha^{-1}$ greater in the mulch/tillage treatments than in the CK treatment at all growing-season temperatures (Fig. 5e and f).

Considering both climate variables, stepwise regression suggested that both growing-season precipitation and growing-season air temperature had significant effects on maize yields in the PMR treatment (Table 5). Only temperature had a significant effect on the maize yield when grown on flat plots (SMF and PMF). Neither precipitation nor air temperature had any significant effect on yield in the SMR treatment. Both precipitation and air temperature had significant effects on maize yield in the no mulch (CK) treatment, and the variation explained by

Fig. 1. The geographical distribution of the sites of the field experiments across the central and northern China included in the meta-analysis (see Table S2 in Supplementary Information for detailed site information).

the two climate variables was higher than in the mulching treatments (Table 5). This is due to the CK being more easily affected by the environment than the mulching treatments.

3.3. Yield response ratios across the precipitation and temperature gradients

When mulched with plastic (PMF and PMR), 98% of the response ratios [i.e. the effect of mulch relative to the check (CK) in each individual study, $\ln R_i$] were positive, while only 2% were negative (Fig. 6). Under straw mulch (SMF and SMR), the majority (93%) of the response ratios were also positive (Fig. 6). When the different mulch treatments were analyzed separately, the response ratios decreased with growing-season precipitation in the plastic-mulch treated plots PMF ($P < 0.05$, Fig. 6b), and PMR ($P < 0.05$, Fig. 6d), but not in the SMF and SMR treatments (Fig. 6a and c). The yield response ratio also decreased with mean growing-season temperature with plastic mulch, both in the flat ($P < 0.05$, Fig. 7b) and ridge-furrow plots ($P < 0.0001$, Fig. 7d), but not in the straw-mulched plots (Fig. 7a and c). The response ratios on average were 0.13 (13% higher than the check treatment) for SMF and 0.11 (11% higher than the check treatment) for SMR across the precipitation and temperature gradients (Figs. 6 and 7).

The results showed that the benefits in terms of yield of using plastic-film mulch on either flat or ridged soil were considerably greater at colder and drier sites than at warmer and wetter locations. With the increase of growing-season precipitation and temperature, the positive effects of plastic mulch and ridge-furrow tillage decreased. The yield benefits of plastic mulch over no mulch approached zero at a growing-season precipitation of about 680 mm under PMF, and 860 mm under PMR (mean 770 mm) and mean growing-season temperatures of about 23 °C under PMF and 25 °C under PMR (mean 24 °C). As the benefits of straw mulch over the CK treatment were not affected by either mean growing-season precipitation or temperature, the yield benefits of plastic-film mulch were lower than those of straw mulch in favorable

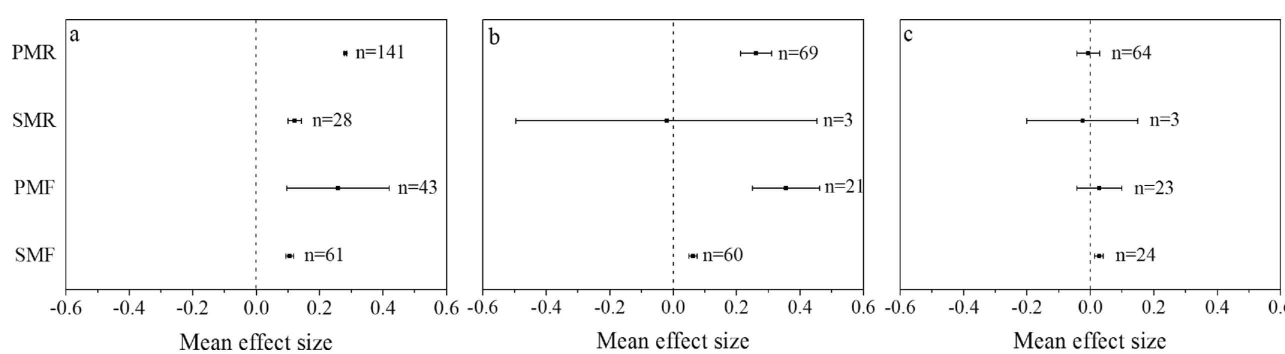

Fig. 2. Mean effect size of (a) yield, (b) water-use efficiency, and (c) evaportranspiration calculated using meta-analysis for straw mulch on flat plots (SMF), straw mulch on ridge-furrow plots (SMR), plastic-film mulch on flat plots (PMF) and plastic-film mulch on ridge-furrow plots (PMR). The number of observations (n) was shown for each treatment. Bars are the 95% confidence intervals (CI). In meta-analysis, the mean effect size was considered significant if the 95% CI > 0, and the mean effect size of two treatments was considered significantly different if the 95% CI of the treatments do not overlap each other.

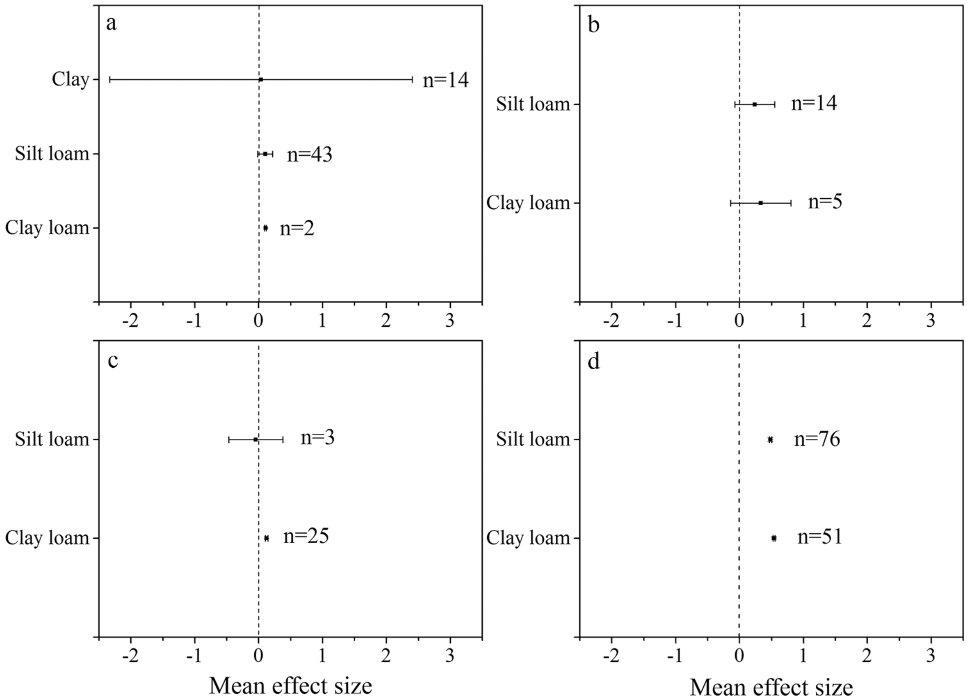

Fig. 3. Mean effect size of maize yield calculated using meta-analysis for different soil types. (a) Straw mulch on flat plots (SMF), (b) plastic-film mulch on flat plots (PMF), (c) straw mulch on ridge-furrow plots (SMR) and (d) plastic-film mulch on ridge-furrow plots (PMR). The number of observations (n) was shown for each treatment. Bars are the 95% confidence intervals (CI). In meta-analysis, the mean effect size was considered significant if the 95% CI > 0, and the mean effect size of two treatments was considered significantly different if the 95% CI of the treatments do not overlap each other.

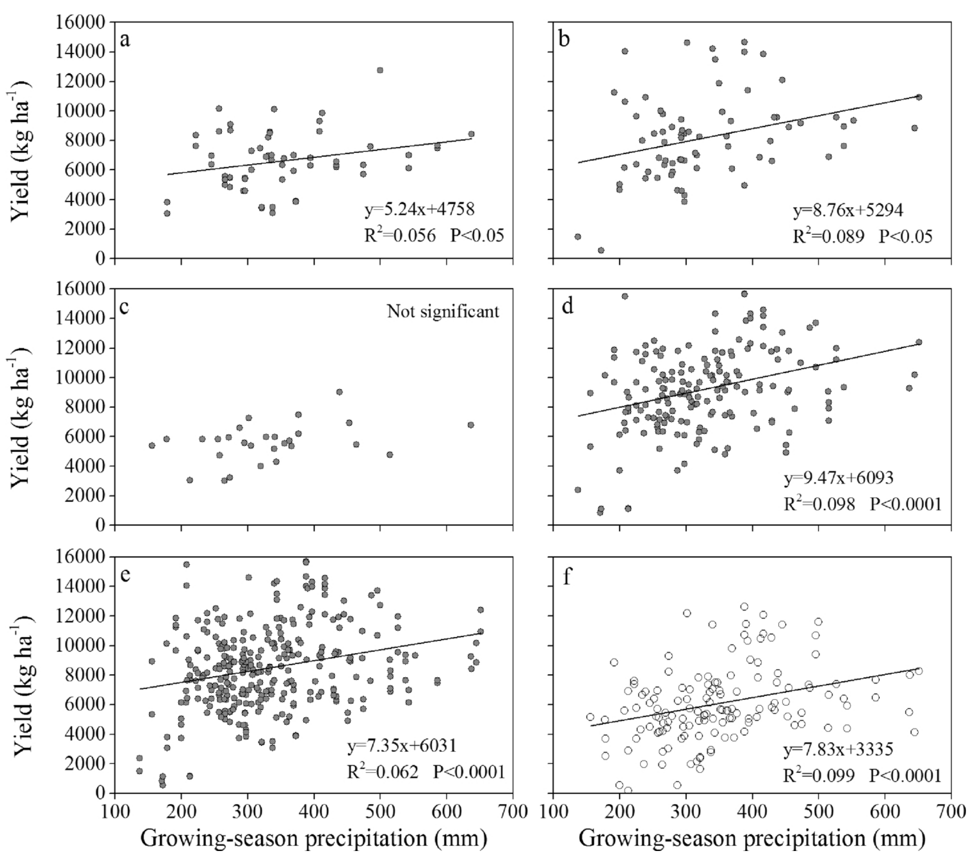

Fig. 4. Relationship between grain yield and growing-season precipitation in the five mulch and tillage practices: (a) straw mulch on flat plots (SMF), (b) plastic-film mulch on flat plots (PMF), (c) straw mulch on ridge-furrow plots (SMR), (d) plastic-film mulch on ridge-furrow plots (PMR); (e) the combination of SMF, PMF and PMR; (f) all check (CK) plots.

environments of precipitation and temperature where plastic-film mulch was no longer beneficial.

Considering both climate variables, stepwise multiple regression suggested that the yield response ratios decreased linearly with growing-season precipitation and mean growing-season air temperature ($P < 0.0001$) in the PMR treatment, whereas only temperature had a significant effect on the yield response ratio in the PMF treatment (Table 6). With straw mulching, no significant relationship was observed with either growing-season precipitation or temperature.

3.4. Effects of mulch and tillage on soil water and soil temperature

To explore the underlying mechanisms of the mulch and tillage practices on the crop, the effects of the treatments on soil water content

Table 4
Results of the analysis of covariance to compare regression equations for mean growing-season precipitation and yield, and mean growing-season temperature and yield, among different treatments and checks: (i) straw mulch on flat plots (SMF), (ii) plastic-film mulch on flat plots (PMF), (iii) straw mulch on ridge-furrow plots (SMR), (iv) plastic-film mulch on ridge-furrow plots (PMR), and (v) no mulch on flat plots (CK) (see Figs. 3 and 4 for the data and linear regressions). The results of SMR were not shown because the yield was not significantly related to either precipitation or temperature under this treatment. Treatments with different letters are statistically significant at $P = 0.05$ level.

Treatment	Precipitation–yield regressions		Temperature–yield regressions	
	Slope	Intercept	Slope	Intercept
CK	a	a	a	a
SMF	a	a	a	a
PMF	a	b	a	b
PMR	a	c	a	c

and soil temperature were analyzed. Both the plastic mulch and straw mulch treatments increased the soil water content compared to the non-mulched flat-plot CK (Fig. 8a). The ridge-furrow plastic mulch treatment (PMR) was the most effective, increasing the soil water content by 1.5% across the growing season. PMF increased the soil water content by 1.2%, SMF by 0.9% and SMR by 0.4%, but there were no significant differences among these three treatments (Fig. 8a). The plastic mulch also increased the soil temperature, and the increase was much greater in the early growth stages of maize from sowing to large bell stage [V12, the twelfth leaf fully unfolded, and the ear in the flower differentiation stage (Lee, 2011)] (Fig. 8b). In the early growth stages, plastic mulch (PMR and PMF) increased soil temperature by about 2.3 °C, but this fell to about 0.5 °C in the later growth stages.

Table 5
Stepwise multiple regression of maize grain yield versus mean growing-season precipitation (P) and mean growing-season air temperature (T) with straw mulch on flat plots (SMF), plastic-film mulch on flat plots (PMF), straw mulch on ridge-furrow plots (SMR), plastic-film mulch on ridge-furrow plots (PMR) and no mulch on flat plots (CK) (the combination of all CK).

Treatment	Regression equation	R^2	*P*-value
SMF	442.5T-2158	0.17	< 0.05
PMF	677.5T-4045	0.21	< 0.0001
PMR	356.0T + 8.3P + 14.1	0.15	< 0.0001
CK	455.3T + 6.2P-4775	0.25	< 0.05

4. Discussion

The meta-analysis has shown that both straw and plastic mulch significantly increased maize yield with plastic mulch being more effective than straw mulch (Fig. 2). Plastic mulch and straw mulch also significantly increased WUE, except in the very limited number of studies on straw mulch on ridges. Similar to a previous study (Wang et al., 2018), the effect of plastic mulch on ET was minor. Only straw mulch had a positive effect on ET of flat plots (Fig. 2). The plastic mulch warmed the soil, particularly during vegetative growth, and both straw and plastic-film mulch increased the soil moisture during the growing season (Fig. 8). Yield increases per unit increase in mean growing-season precipitation and air temperature were similar across mulch, tillage and check treatments, but yields were consistently higher in the plastic mulch plots, PMF and PMR, than in CK at all levels of growing-season precipitation and temperature (Table 4).

Low temperatures in the root-zone severely impair emergence and crop development, and can even cease maize growth (Imran et al., 2013; Barber et al., 1988; Wang et al., 2018). The warming of the soil by the plastic mulch, particularly during early crop development,

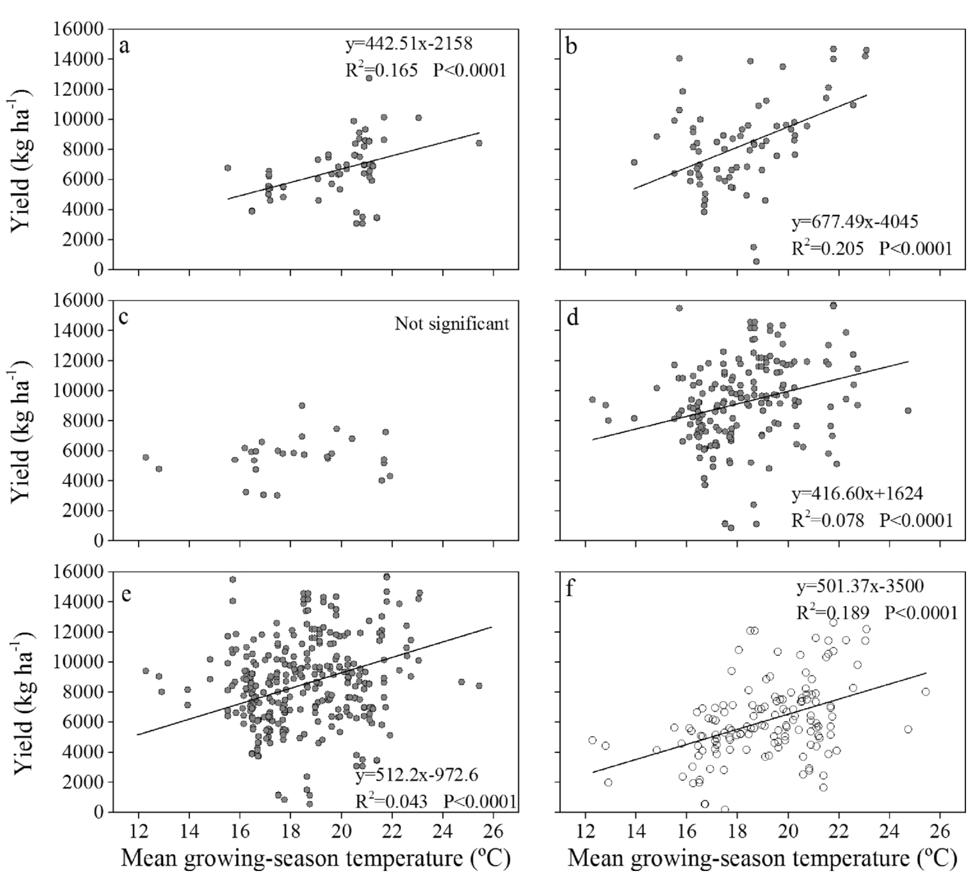

Fig. 5. Relationship between grain yield and mean growing-season air temperature in the five tillage and mulch practices: (a) straw mulch on flat plots (SMF), (b) plastic-film mulch on flat plots (PMF), (c) straw mulch on ridge-furrow plots (SMR), (d) plastic-film mulch on ridge-furrow plots (PMR), (e) the combination of SMF, PMF and PMR, and (f) all check (CK) plots.

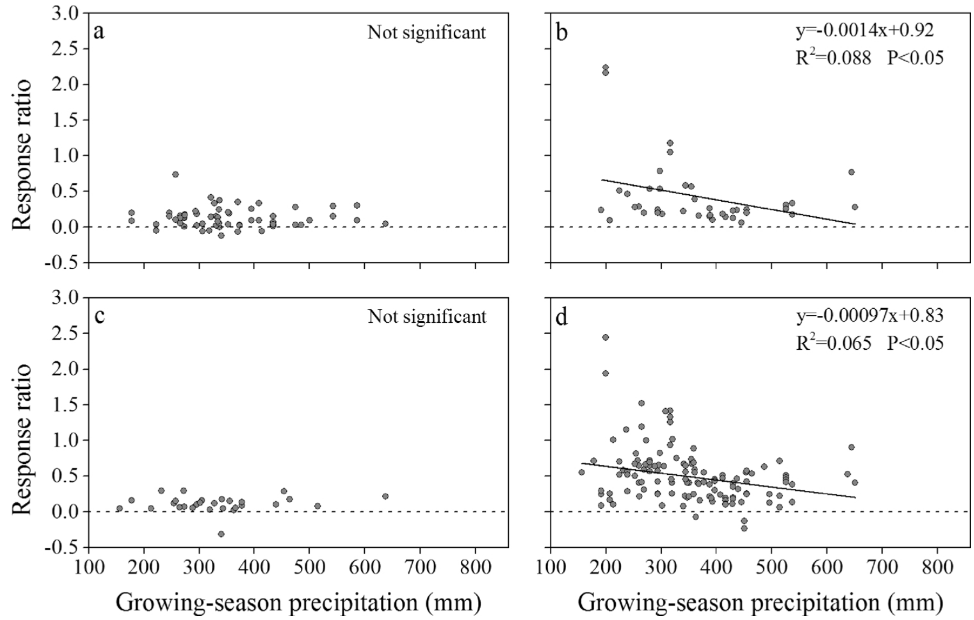

Fig. 6. Relationship between yield response ratio (lnR_i, calculated in the meta-analysis) and growing-season precipitation with (a) straw mulch on flat plots (SMF), (b) plastic-film mulch on flat plots (PMF), (c) straw mulch on ridge-furrow plots (SMR), (d) plastic-film mulch on ridge-furrow plots (PMR).

certainly increased the maize yield. Straw and plastic mulch can also reduce soil evaporation and improve water use efficiency (Chen et al., 2007), as observed in this study. However, in poorly-drained soils or cool climates with suboptimal spring temperatures, straw mulch can reduce yields due to decreased soil temperature compared to no-mulch (Wang and Shangguan, 2015). As the soil types were mostly loamy and well drained (Gong, 1999) in most of the study sites in our analysis, straw mulch had positive effects on maize yield and water use efficiency. While straw mulch has mainly been implemented alongside conservation tillage to reduce soil erosion (Shao et al., 2016), straw mulch may not only increase maize yields in the short term, as observed in this analysis, but may have significant long term benefits by increasing or maintaining soil organic carbon (Cadavid et al., 1998; Rusinamhodzi et al., 2011; Wang et al., 2016b). In our analysis the positive effects of plastic and straw mulch and ridge-furrow on maize

Table 6
Stepwise multiple regressions of yield response ratios versus mean growing-season precipitation (P) and mean air temperature (T) with plastic-film mulch on flat plots (PMF) and plastic-film mulch on ridge-furrow plots (PMR). No significant linear function was found in the straw mulching treatments (straw mulch on flat plots and straw mulch on ridge-furrow plots).

Treatment	Regression equation	R^2	*P*-value
PMF	$-0.1T+2.6$	0.22	< 0.05
PMR	$-0.067T-0.001P+2.003$	0.18	< 0.0001

yield were higher for clay loam than for silt loam, which is probably due to higher water storage capacity in clay loam than in silt loam soils. Therefore, we suggest that soils with an intermediate drainage/water

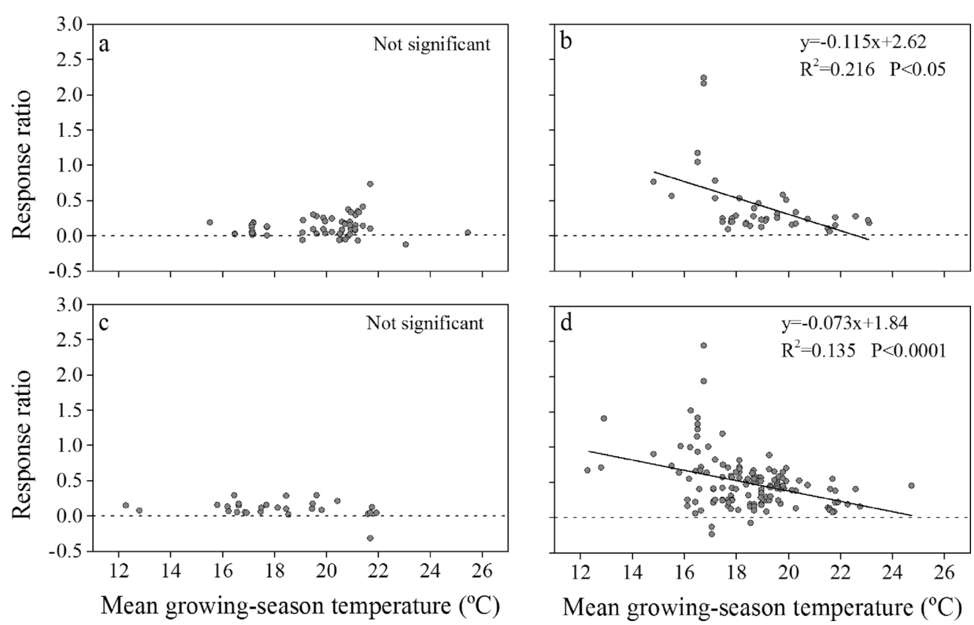

Fig. 7. Relationship between yield response ratio (lnR_i, calculated in the meta-analysis) and mean growing-season air temperature with (a) straw mulch on flat plots (SMF), (b) plastic-film mulch on flat plots (PMF), (c) straw mulch on ridge-furrow plots (SMR), and (d) plastic-film mulch on ridge-furrow plots (PMR).

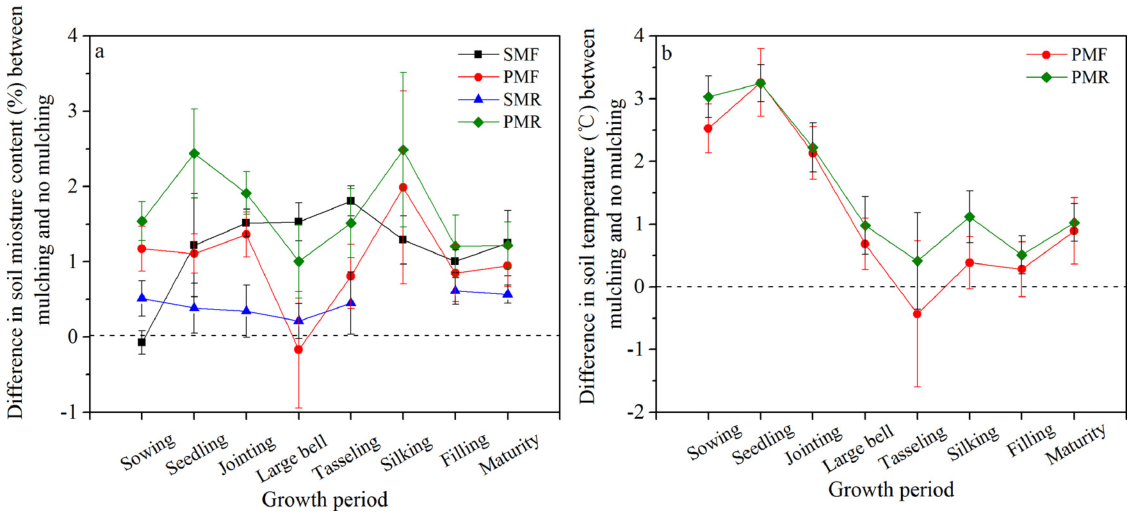

Fig. 8. Differences in (a) soil moisture (gravimetric water content in %) and (b) soil temperature (°C) between the no-mulch flat check plots and (i) straw mulch on flat plots (SMF), (ii) plastic-film mulch on flat plots (PMF), (iii) straw mulch on ridge-furrow plots (SMR), and (iv) plastic-film mulch on ridge-furrow plots (PMR) during the different growth stages of maize. Soil water data: $n = 79$ for SMF, $n = 149$ for PMF, $n = 21$ for SMR, $n = 248$ for PMR; soil temperature data: $n = 79$ for PMF, $n = 182$ for PMR (no temperature data available for SMF and SMR). Error bars are ± one standard error of the mean.

storage capacity are likely to be most suitable for plastic mulching as poorly-drained soils have lower soil temperatures and are slower to warm up in spring, while highly-drained soils have lower soil water storage and any additional water is likely to be lost by deep drainage.

Compared with straw mulch, plastic film mulch has been shown to significantly reduce soil evaporation and erosion, maintain soil moisture, suppress weeds, improve soil temperatures and decrease cold stress, and thus increase yields and improve water use efficiency (Liu et al., 2014; Sui et al., 1992; Liu et al., 2010; Zhou et al., 2009). Both field and modeling studies have suggested that plastic film mulching has the potential to reduce soil N_2O emission (Berger et al., 2013; Kim et al., 2015) and nitrate leaching (Kim et al., 2015; Wang and Xing, 2016), and thus improve the available nitrogen in the soil (Wang and Xing, 2016). While plastic mulch decreases in-season urea-N uptake and urea-N loss, it increases the retention of urea-N in maize-cropped soils (Liu et al., 2015). Similar to previous meta-analyses (Wang and Shangguan, 2015; Zhang et al., 2017), our comparisons among the five management practices indicated that plastic mulch combined with ridge-furrow technology (PMR) was the most effective in increasing soil water (Fig. 8) and grain yield (Fig. 2), and equally effective with PMF in increasing soil temperature (Fig. 8). In addition to reducing soil evaporation and increasing soil temperature, the practice also channels rainfall to the furrows and root zone through perforations in the plastic mulch (Jiang and Li, 2015) which also provides a benefit in clay soils with less risk of deep drainage.

The positive effects of plastic mulch diminished with increasing growing-season precipitation and temperature, while the benefits of straw mulch remained stable across the temperature and precipitation gradients (Figs. 6 and 7). Thus, the plastic mulch significantly increased the grain yields at the low precipitation and temperature sites, but the practice becomes unnecessary to boost yields where hydrothermal conditions were more favorable for crop growth (Wang et al., 2016a; Ye and Liu, 2012). Furthermore, mulch needs labor and capital inputs (Liu et al., 2009; Ye and Liu, 2012) and residue plastic from plastic-film mulch may cause soil pollution (Yan et al., 2014). Therefore, the use of plastic mulch should be limited to unfavorable hydrothermal environments where the technology provides economic benefits. Extrapolation of the response ratios showed that the yield benefits of plastic-film mulch reached zero when the mean growing-season precipitation 770 mm; taking into account the economic and environmental costs of plastic-film mulch would lower the mean growing-season precipitation at which the benefits reach zero. Our results also show that the benefits (response ratios) to maize yield of plastic mulch decreased with temperature (Fig. 7), reaching zero at a mean growing-season temperature of about 24 °C, suggesting that future warmer climates will reduce the need for plastic-film mulch in areas where it is currently widely used (Wang et al., 2016a). Similarly, the positive effects of ridge-furrow tillage also decreased with increasing growing-season precipitation and temperature (Figs. 6 and 7). However, there was no significant change in the yield benefit of the straw mulch treatments with mean growing-season precipitation and air temperature, suggesting that straw mulch will provide a small (mean 12%) increase in yield compared with the control treatment across the full range of growing-season precipitation (150 to 600 mm) and temperatures (12 to 25.5 °C) in the regions of the analysis.

Although several recent meta-analyses (Qin et al., 2015; Wang and Shangguan, 2015; Zhang et al., 2017) have been conducted to evaluate the optimal mulch and tillage practices, our analysis is the first to show that the effects of straw- and plastic-film mulch decrease linearly (and significantly in most treatments, particularly with plastic mulch) with an increase in mean growing-season precipitation and temperature. We explicitly suggest the precipitation and temperature conditions at which the effects of plastic mulch do not exceed those in the non-mulched flat plots (Figs. 6 and 7). We suggest that our analysis is useful for selecting the appropriate crop field management practices to improve maize yield across a wide range of hydrothermal gradients.

5. Conclusion

Our analysis has shown that straw and plastic mulch and ridge-furrow practices improved soil hydrothermal environments and thus increased maize grain yield and water use efficiency across northern China. Straw and plastic mulch increased soil moisture during all growth stages of maize, while plastic mulch also increased the soil temperature, particularly during early growth, thereby speeding the emergence and early development of the maize. While the effects varied with soil type, the ridge-furrow plastic mulch system had the greatest increase in soil water content, soil temperature and grain yield compared with the non-mulched treatment on flat soil. As the hydrothermal gradients became warmer and wetter the benefits of straw mulch did not change significantly, whereas the positive effects of plastic mulch on maize yield decreased across the temperature and precipitation gradients. We conclude that plastic-film mulch should be limited to unfavorable hydrothermal environments where the technology

provides yield and economic benefits. This study also suggests that with global warming, the widespread area over which plastic mulch provides yield benefits will grow smaller or will move to higher latitudes in the northern hemisphere.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2018.07.005.

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